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ICOSSAR 2005, G. Augusti, G.I. Schuëller, M. Ciampoli (eds)
 ISBN 90 5966 040 4

Non-linear structural analysis for *in-situ* platform demolition

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Keywords: Offshore platform decommissioning, non-linear structural analysis, behavior to collapse, underwater cut.

The abandonment of offshore platforms is an interesting engineering field, both regarding the operating methodologies connected with technological aspects, and for the structural aspects during the decommissioning phases. Specific abandonment plans must be studied for every installation in order to assure the safety of the identified decommissioning sequence. The structural analyses proposed in the present paper for the proposed decommissioning sequence, are in a non-linear field and they show how it is possible with a proposed sequence to obtain two important results: firstly to reduces the times for underwater cutting operations and, secondly, to assure a sufficient safety margin during the cutting operations.
This paper becomes part in the tradition of studies inherent the offshore platforms decommissioning, proposing one preferred abandonment methodology for the steel jacket platforms, carried out by cutting the structural members, in a safe sequence.

1 INTRODUCTION

Offshore steel platform abandonment is performed under a specified pre-determined sequence, Coleman (1995). The study of cutting sequences needs to guarantee safety during marine operations for specific environmental conditions, E&P Forum (1996).

The aim of this study is to investigate the behavior of the Vega A offshore platform (an eight-leg steel jacket platform, operating in the Sicily Channel, 25 km offshore in 122.3 m water depth) until it collapses under different sea states, and for defined boundary conditions.

A cutting sequence for the jacket columns, that ensures the safety of under- water operations, has been defined. The procedure for the platform abandonment analyzed in this paper, envisages cutting for main columns at the depth of 55 meters below the Lowest Astronomic Tide (or LAT for short) before to proceed with the bracings cutting. This cutting sequence is preferred to the dual one (first cutting the bracing members and then the columns), because the columns cut takes more time, and it's a very delicate operation: the bracing members assure the stability of the structure under wave and current loading.

The study was carried out using a non-linear numerical analysis where one assume, for the columns object of the cutting operation, a residual compression resistance (no-tension structural elements). The non linear approach for this problem better describes the structural conditions during the cutting operation (due to the presence of the mono-lateral supports) then the usual linear analyses. As a matter of act, normally, no residual resistance is assumed for the cut elements: they are not considered in the numerical analysis.

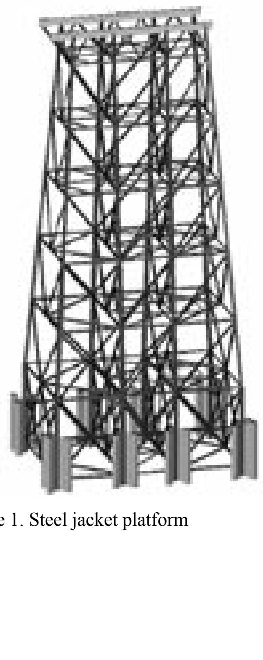

Figure 1. Steel jacket platform

The innovative nature of this approach is underlined by the use of gap elements to model cuts in structural members. These kinds of elements, which normally have been used in different engineering fields, assure for the connected elements the transmission of the compression and shear force, but not the tension through the legs of the platform during abandonment phases. The ability of the cuts to transmit normal compression stresses and shear action is due to friction between surfaces which could stay in contact.

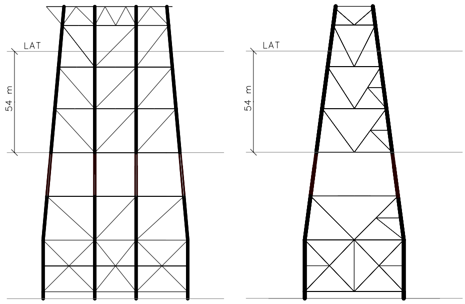

Figure 2. SASP demolition phase: vertical bracing cut

The ultimate loading on the platform is computed using a step-by-step incremental analysis, modeling the cuts and modifying the original structural static scheme. The analysis is carried out by modeling the structural elements using a finite element program. Even though this approach is heavy from a computational point of view, it allows one to better estimate the behavior of the platform under a specific sea state, otherwise not possible using linear analyses. A preliminary sensitivity analysis is carried out within two extreme conditions based in the limit analysis in order to have a range of acceptable values, Franciosi (1979).

The aim of this analysis is to identifies a cutting sequences compatible with the safety during marine operations for the environmental conditions when the cutting in active members is done. The results have shown the feasibility of the proposed cutting sequence, that gives two important advantages resulting in less time for the cutting and greater safety during cutting.

The Vega A platform comprises a steel Jacket platform (Fig. 1), which is 140 m high, having eight columns connected using horizontal bracings with four vertical bracings in the transversal direction and two vertical bracings in longitudinal direction. The dimensions of the jacket at the sea bed are 70 m by 48 m, while at the top they are 50 m by 18 m, Musso et al. (1996). Six horizontal bracing frames, spaced at approximately 24 m, are also used to support the well conductor guides. The jacket is supported by 20 vertical steel piles, 85 m long with a diameter of 2.6 m. These piles have been driven to a depth of 65m below the seabed by means of an underwater hammer. Since March 1988 the platform structural behavior has been object of study by the University of Florence. A system of vibration monitoring is active on the platform, which records many types of structural data, Galano et al. (1996).

Moreover a comparison between present results, discussed in the following, has been made with a linear study, SASP Offshore Engineering (1998). This study analyses the evaluation of the collapse strength of the platform, for the hypothesis of complete removal of the vertical bracing by cutting at -55 meters (Fig. 2). The design assumptions used in the SASP linear analysis are as follows: Wave: Hs = 4.6 m, Hmax = 8.5 m, Tp = 10 s; Wind = 25 m/s; Current = 1.07 m/s; Marine growth = 50 mm. The wave is applied by three directions, the first is W101, 0° degree (parallel the X-axis), the second is W201, 41° degree, and the last is W301, 90° degree (parallel Y-axis). The horizontal forces transmitted by waves motion, at the level of –55 to the LAT, are 391 ton in the longitudinal direction and 438 ton in the transversal direction.

2 PROPOSED DEMOLITION SEQUENCE

The demolition sequence investigated in this paper provides, for the decommissioning of the offshore platform, an underwater cutting at a level of –55 meters (in order to leave a water depth of 55m approximately from the LAT). Consequently, the lower part of the platform will remain submerged leaving a sufficient water column to ensure safe navigation (Fig. 3).

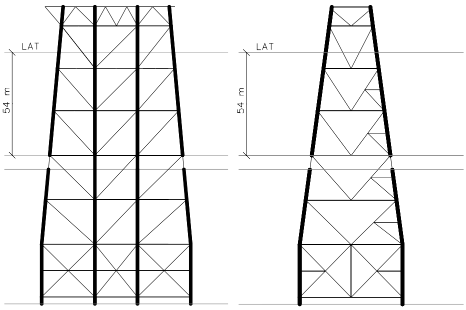

Figure 3. Demolition phase: columns cut

The cuts will be carried out in two successive phases. In the first phase, the jacket columns are cut between level -55 m and -75 m. Subsequently, the elimination of the remaining connections between the vertical bracing elements connecting the two parts is carried out. This cut sequence is preferred to the other possible sequences essentially for the criticality of this structural phase of the platform demolition, Blair-Fish et. Al. (1996). The analysis results confirm the virtue of this operative sequence where the cutting of columns is preferred to the cutting of the bracing elements because after cutting the columns, the structure is still able to transmit the wave loading for the given environmental conditions. This result is extremely important since the abandonment of the platform can be done in a limited time window where it's possible to assume a specific limited sea state.

For finalize the decommissioning phases, and remove completely the upper part of the platform, it is possible to use a remotely operated system, which can be, for example, the use of explosives or similar. After the complete separation of the two parts has been carried out, the upper part could be laid on the sea bottom, which does not constitute an obstacle to navigation, or could be totally removed.

3 NON LINEAR FEM MODEL

For the numerical analysis of the removal hypothesis developed in this work, it has been used a specific element to model the columns cut, the gap element Ansys (1990).

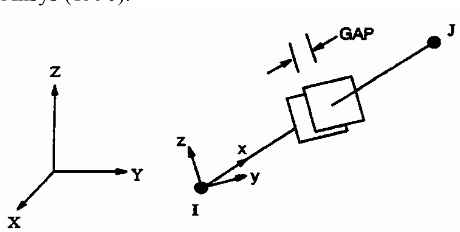

Figure 4. Point-to-point contact element

This element represents two surfaces (Fig. 4) which may maintain or break physical contact and may slide relative to each other. It is capable of supporting only compression in the surfaces normal direction and shear (upon Coulomb friction law) in the tangential direction.

4 NON LINEAR STRUCTURAL ANALYSIS

The modeling of the structure, because the innovative nature of the non-linear analyses, has been intentionally simple. With the intention to offer an appraisal method that, even though sophisticated for the type of analysis, allows a fast valuation of the last resistance it is preferred to perform the first approximation with a two dimensional model of the structure. A second simplification for the model concerns the loads. Rather than representing the wave loading with its effective distribution it has been preferred to apply a deterministic load. This hypothesis allows, moreover, a comparison with the linear study carried out by SASP Offshore Engineering. Other analyses could be carried out to enhance the model in order to consider the structure in its complete three-dimensional development with a load distribution that faithfully reproduces the marine action, Darbyshire and Draper (1963).

In the longitudinal direction the jacket is a structure with four principal columns tapered in height, with horizontal bracings spaced approximately every 24 m, and rectilinear vertical bracings (Fig. 5). Non linear analyses have been carried out on the 2D simplified model using the F.E. computer code ANSYS. Main columns and vertical and horizontal bracing elements have been modeled by means of pipe elements, while gap elements have been used to model cut hypothesis. The 2D model (longitudinal direction) consists of 50 joints, 94 2D elastic-pipe elements and 4 gap elements.

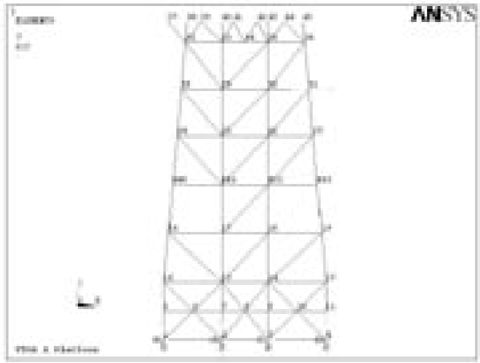

Figure 5. 2D Model: x-z plane

In the envisaged cutting sequence for the platform decommissioning it is required to leave a depth below the LAT of approximately 55 m. This means that in the longitudinal direction it has been investigated the contribution to the collapse load offered from the bracing between -55 m and -75 m . A series of modeling that have characterized by different cutting sequences of the bracings have analyzed.

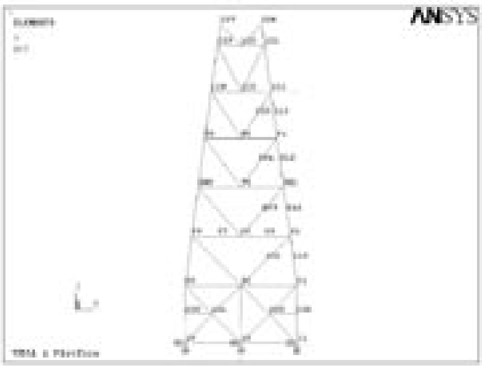

Figure 6. 2D Model: y-z plane

After the columns cut some hypothesis concerning the vertical bracing removal have been analyze. The first implemented hypothesis concerns the removal of the external vertical bracings: first is removed the one in tension, and then the one in compression; finally both are removed leaving only the central vertical bracing. The situations investigated in longitudinal direction are then the following:

Table 1. Analysis cases (Longitudinal model)

L.1	Columns cut to the level of -55.0 m with respect to LAT, with removal of one bracing (tensile diagonal)
L.2	Columns cut to the level of -55.0 m with respect to LAT, with removal of one bracing (compressed diagonal)
L.3	Columns cut to the level of -55.0 m with respect to LAT with removal of two bracing

In the transversal direction the jacket is a structure with two principal columns with horizontal bracings (Fig. 4). The cuts in the principal columns always are scheduled under the joints of the structure (where the section in not strengthened), to a level of, approximately, -55 m from the LAT. In this direction moreover it has studied the behavior of the structure, with respect to the limit loads, as a function of the depth of the cut. The investigated cases are then the following:

Table 2. Analysis cases (Transversal model)

T.1	Columns cut to the level of -33.0 m with respect to LAT
T.2	Columns cut to the level of -55.0 m with respect to LAT

An analogous model has been developed for the transversal direction in order to analyze the same load directions (directions W101 and W301) analyzed by SASP Offshore Engineering (1998). The 2D model for this transversal direction consists of 19 joints, 63 2D elasto-plastic pipe elements and 2 gap elements.

It has been analyzed moreover a limit situation concerning the cut and complete removal of the principal columns; the results are discussed in the following.

The analyses, in addition to the use of the gap elements, assume an elasto-plastic behavior for the elements (differing again from the elastic behavior assumed by previously mentioned work). A perfectly plastic elastic behavior for these elements has been assumed to take into account the possibility, when the material elasticity threshold is exceeded, to store plastic deformations.

4.1 *Numerical results*

With respect to the first investigated hypothesis (wave loads acting in the longitudinal direction), which envisaged columns cut to level -55 m below LAT with the removal of a single bracing, the structure becomes a mechanism at load step 69. The corresponding action applied to the structure is about 1360 ton.

The second hypothesis (cutting the columns to a level of –55 m below LAT with removal of the bracing opposite to the first one) sees the construction become a mechanism with a collapse actions of 780 ton corresponding at load step number 40.

Finally, the last investigated case in the longitudinal direction holds the greatest interest, it studies the complete cutting of columns, always to -55 m below LAT, with the removal of both the vertical bracings; Fig. 3 shows the adopted modeling. The boundary conditions and the loads applied on the structure are showed in figure. The load, in particular, is a unitary horizontal load applied at sea level, it increases until the structure collapses.

It has been found that the structure becomes a mechanism at load step 68 (Fig. 7), when the applied load is equal to 268 ton.

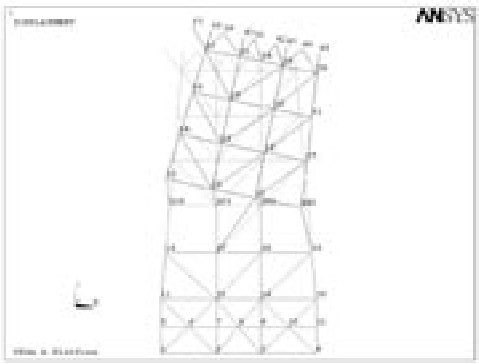

Figure 7. Deformation of the jacket in longitudinal direction (x-z plane) before the collapse.

The figure shows the deformation immediately prior to collapse. The separation of principal columns where gap element have been introduced is visible. The behavior of the columns in compression is also shown. At load step 68 the mechanism that it is accountable for the collapse of the construction it is the side-slip of the compressed columns. The horizontal displacements of the columns, towards the inner part of the structure, produce the overturning of the jacket.

The introduction of gap elements for the modeling of the column cuts allow to study the total behavior of the structure in the limit state. Even after the cuts the compressed columns are able to continue to transmit compression stresses, contributing to the resistance of the structure. Fig. 6 shows the displacements of the point of application of the load (node 31 in Fig. 5) with respect to the increase load parameter "t" (it represents the phases of monotone increment of the load). The gap elements are responsible for the non-linear relation between displacement and loads. Such form mean that the structure reaches the point of collapse with increasing displacement.

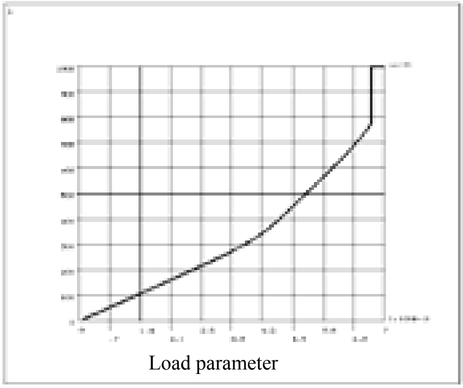

Figure 8. Displacement (mm) of loaded joint.

Table 1 shows the displacement in the horizontal and vertical direction of the end joints of the compressed gap (Fig. 7). Such movements are reported in millimeters. The comparison of vertical movements UZ and horizontals UX of nodes 23 and 123 at the extremities of the compressed gap element (the gap element connected the joint 23 and 123) shows a maximum relative movement in the horizontal direction equal to 4,8 millimeters. This value is reached just before collapse. As the dimensions of the columns are 2000x35 millimeters, then this value guarantees the continued local contact between the compressed columns.

Table 3. Displacements of joints of gap elements

Load parameter	123 UX (mm)	23 UX (mm)	123 UZ (mm)	23 UZ (mm)
.01000	-5.60064	-5.65131	-.599504	-.601858
.10000	-56.2137	-56.7189	-6.07711	-6.10059
.15000	-84.4934	-85.2498	-9.18468	-9.21987
.20000	-112.888	-113.895	-12.3389	-12.3858
.25000	-141.398	-142.655	-15.5402	-15.5987
.30000	-170.023	-171.528	-18.7890	-18.8591
.35000	-200.592	-202.366	-22.2695	-22.3514
.40000	-233.129	-235.193	-25.9904	-26.0840
.45000	-275.632	-278.099	-30.7848	-30.8906
.50000	-327.384	-330.362	-36.6254	-36.7435
.55000	-379.461	-382.949	-42.6194	-42.7497
.60000	-432.050	-436.052	-48.7895	-48.9319
.65000	-496.765	-501.268	-56.7496	-56.9039
.66000	-512.530	-517.130	-58.6285	-58.7851
.67000	-529.465	-534.163	-60.6876	-60.8466
.68000	-548.253	-553.058	-63.0036	-63.1649

In transversal direction two analysis has been conducts. The first one examines the cut at depths of -33 m. For this hypothesis result has been that the structure becomes a mechanism at load step 64. The corresponding applied load is 252 ton.

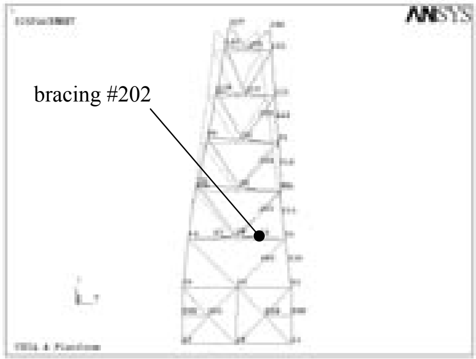

Figure 9. Deformation of the jacket in the transversal direction,

The second case, the most interesting, examines the cut at depth of -55 m (corresponding to the horizontal plane immediately under the previous hypothesis). In this case it has been determined that the construction becomes a mechanism at load step 64 (Fig. 9).

The corresponding applied load is 126 ton. Fig. 7, shown the displacement of the jacket in the transversal direction with respect to the load step immediately prior to collapse. At the load step following, the mechanism has been originated and the structure begins to rotate.

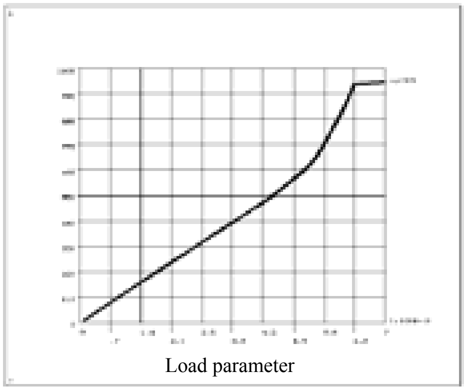

Figure 10. Displacement (mm) of loaded joint

Fig. 10 shows the displacement, in millimeters, of the point of application of the load. In abscissa the increase parameter "t" it represents the phases of monotone increment of the load. At the beginning the behavior is substantially linear, and it remain almost linear up to the collapse of the structure. The linearity of the first section is due to the presence of the horizontal bracing at -75m: it acts as an elastic spring for bracing number 202 of Fig. 9. After that, the horizontal bracing looses it's elastic properties because it reaches the yield stress, the structure then rapidly collapses.

Comparing Fig. 7 with Fig. 9 it's possible to see how, in the two main directions the collapse of the structure happens through the formation of a mechanism. This mechanism is due to different behaviors. In the first case analyzed, loads acting in longitudinal direction, the behavior is non-linear since the first phases of application of loads, and the horizontal bracings does not play an essential role in the determination of the ultimate collapse load.

For the second load case investigated, loads acting in transversal direction, instead it is exactly the presence of the horizontal frame at –75 m that determines the collapse load. The horizontal frames are responsible for the linearity of the first sequence of the diagram show in Fig. 8. They act as a linear elastic spring and the structure quickly reaches collapse after failure of horizontal bracing. Fig. 11 shown the opening of the gap, in millimeters, against the parametrical increase of the load. The gap opening represents the separation of the two surfaces of Fig. 4. The diagram has the same slope as in Fig. 10 and it confirms the mode of collapse that it has been described.

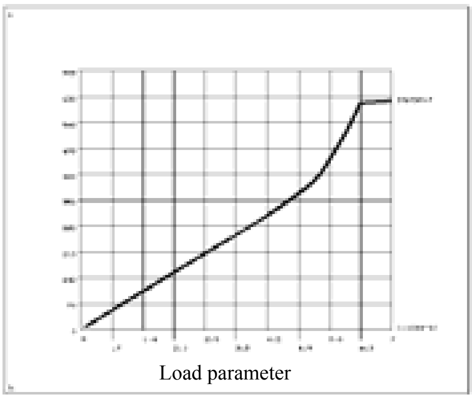

Figure 11. Gap opening (mm)

A simplify plane 2D-modeling for the two main directions (longitudinal and transversal) of the jacket, it has allowed to characterize clearly these two different behaviors. They are obviously always related to the particular abandonment sequence under investigation, and also, of course, to the particular structural shape of the platform analyzed.

Substantially it is possible to assert that the elimination of the principal columns without the removal of the bracing, that are still connected with the node, permit a redistribution of the forces in the structure from the columns to the bracing that, for the examined load condition, leave to the structure a residual resistance with respect to the loads.

A final analysis for studying the limit situation of the complete removal of the columns, with respect to the longitudinal loads, is carried out. In this hypothesis the columns are not able to transmit compressive loads: they are completely removed by the numerical model. For this case it has been found that the structure collapses at load step 8. A load of 14 ton, considerably less than 126 ton, ultimately confirms the validity of this simplify non-linear approach. The non-linear analysis permits a better estimate of the contributions of the resistance of the columns, also after that they have been cut.

4.2 *Comparison between results*

Following figure shows the results of the non-linear analyses for the cutting sequence analysed with respect to the SASP results obtained for the removal hypothesis illustrated in Fig. 2:

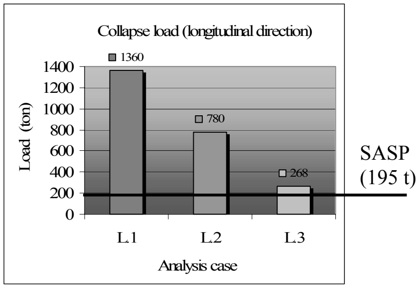

Figure 12. Collapse load in longitudinal direction

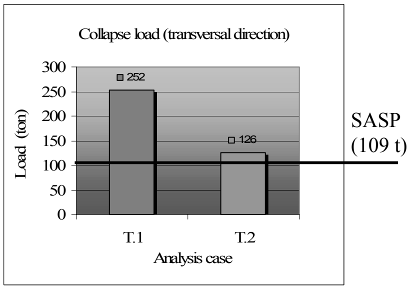

Figure 13. Collapse load in transversal direction

It has been assessed the loads that the Vega A Jacket is able to transmit before reaching collapse. These values have been determined in the hypothesis that, after the columns have been cut, they are still able to transmit compression loads. This hypothesis is in effect compatible with the effective physical behavior of the columns. Confronting these results with the values of the loads obtained from the SASP linear analysis, it has been found in longitudinal direction a collapse load of 268 ton against a load of 195 ton. In the transversal direction the collapse load is 126 ton against a wave load of 109 ton.

These results have shown the advantages of the presented cutting hypothesis, in terms of safety for the underwater cut. The more critical operation, that is the cutting of the columns is made at a time when the structure is able to support a higher wave loading.

5 CONCLUSION

In recent years numerous offshore platforms have reached the end of their useful life and therefore their abandonment has become necessary. Their demolition and transportation to land, or abandonment in the sea, necessitates the definition of techniques and sequences of cuts that are compatible with the execution of the marine operations for specific environmental conditions.

This study has proposed a sequence of cuts. A non-linear finite element analyses that allows to estimate with great precision the structural behavior during marine operations. It has produced a numerical modeling of the Vega A jacket by means pipe elements with elasto-plastic behavior and gap elements, without traction resistance, for modeling the cut on the columns.

The introduction of these gap elements, innovative in the study of such structures, has helped to obtain an estimate of the collapse load, for horizontal load applied in proximity of the marine surface, and it demonstrates the validity of the proposed sequence of cuts. From the comparison between the collapse load with wave load it has been found that the proposed sequence offers an adapted safety margin, for the underwater cutting of the columns, in comparison with the actual wave loading.

The proposed sequence consists of the cutting of columns to a level of -55,0 meters LAT immediately under the node stiffness. In the first step it is scheduled to cut only these columns and some bracings member. Then for the complete dismantling of the platform, the remaining bracing, are cut.

This cut sequence has the advantage that the most critical operation, namely, cutting the columns, are done when the integrity of the structure has not been completely compromised. The structure is still able to transfer to the foundations the loads that it will be subject to during the subsequent dismantling operations. The position of the cuts respects the operational necessities, and the structural collapse behavior demonstrates the feasibility and the advantages of this sequence.

From the comparison between the collapse load with wave load it has been found that the proposed sequence offers an adapted safety margin, for the underwater cutting of the columns, in comparison with the actual wave loading.

The analyses of collapse mechanism have permitted a qualitative interpretation of the essential facts that guide the achievement of the crisis in the longitudinal and transversal directions. It has been estimated how in the transversal direction the presence of the horizontal bracing is fundamental to the collapse of the structure, while in the longitudinal direction a role equally important is carried out by the compressed columns.

In consideration of the results it seems useful that further studies of the non-linear analysis are performed with the three-dimensional modeling of the jacket and using the actual distribution of wave and current loading on the structure.

ACKNOWLEDGMENTS

The Authors would like to thank EDISON Spa for supplying the Vega A platform structural data and the results of SASP decommissioning report.

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